
ICE Handbook of Geosynthetic Engineering

ICE Handbook of Geosynthetic Engineering

Geosynthetics and their applications

Third edition

Edited by
Sanjay Kumar Shukla

Published by ICE Publishing, One Great George Street, Westminster,
London SW1P 3AA.

Full details of ICE Publishing representatives and distributors can be found at:
www.icebookshop.com/bookshop_contact.asp

Other titles by ICE Publishing:

Environmental Geotechnics in Practice: Introduction and case studies

Robert Sarsby. ISBN 978-0-7277-6363-1

Polymer Support Fluids in Civil Engineering

Carlos Lam and Stephan A. Jefferis. ISBN 978-0-7277-5786-9

Geotechnical Finite Element Analysis

Andrew Lees. 978-0-7277-6087-6

www.icebookshop.com

A catalogue record for this book is available from the British Library

ISBN 978-0-7277-6500-0

© Thomas Telford Limited 2022

ICE Publishing is a division of Thomas Telford Ltd, a wholly-owned subsidiary
of the Institution of Civil Engineers (ICE).

All rights, including translation, reserved. Except as permitted by the
Copyright, Designs and Patents Act 1988, no part of this publication may be
reproduced, stored in a retrieval system or transmitted in any form or by any
means, electronic, mechanical, photocopying or otherwise, without the prior
written permission of the Publisher, ICE Publishing, One Great George Street,
Westminster, London SW1P 3AA.

This book is published on the understanding that the author is solely
responsible for the statements made and opinions expressed in it and that
its publication does not necessarily imply that such statements and/or
opinions are or reflect the views or opinions of the publishers. While every
effort has been made to ensure that the statements made and the opinions
expressed in this publication provide a safe and accurate guide, no liability or
responsibility can be accepted in this respect by the author or publishers.

While every reasonable effort has been undertaken by the author and the
publisher to acknowledge copyright on material reproduced, if there has been
an oversight please contact the publisher and we will endeavour to correct
this upon a reprint.

Cover photo: Green grass in a plastic black honeycomb frame to prevent soil
erosion on the slope.

Commissioning Editor: James Hobbs

Development Editor: Melanie Bell

Production Editor: Madhubanti Bhattacharyya

Marketing Specialist: April Nagy

Typeset by The Manila Typesetting Company

Index created by Matthew Gale

Printed and bound in Great Britain by TJ Books, Padstow

Contents

	Preface	xi
	About the editor	xv
	List of contributors	xvii
01	Fundamentals of geosynthetics	1
	<i>S. K. Shukla</i>	
	1.1. Introduction	1
	1.2. Definitions and classification	1
	1.3. Historical development	6
	1.4. Basic functions and selection	8
	1.5. Raw materials and manufacturing processes	11
	1.6. Properties and test methods	14
	1.7. Application areas	33
	1.8. Standards	35
	1.9. Summary of the main points	35
	1.10. Common questions and their answers	35
	References	41
02	Soil–geosynthetic interaction	45
	<i>M. L. Lopes and C. S. Vieira</i>	
	2.1. Introduction	45
	2.2. Granular soil behaviour	45
	2.3. Soil–geosynthetic interaction mechanisms	46
	2.4. Soil–geosynthetic interface resistance	47
	2.5. Factors influencing soil–geosynthetic interaction	49
	2.6. Summary of the main points	64
	2.7. Common questions and their answers	64
	References	65
03	Filters and drains	67
	<i>A. H. Aydilek, Y. Zhang and A. Y. Dayioglu</i>	
	3.1. Filters	67
	3.2. Geotextile filters	67
	3.3. Geotextile filtration mechanism	67
	3.4. Factors affecting geotextile filter behaviour	72
	3.5. Laboratory filtration performance tests	75
	3.6. Filter evaluation using image-based methods	77
	3.7. Filtration of high-water-content geomaterials with geotextiles	78
	3.8. Hydraulic compatibility of geotextile filters with industrial by-products	79
	3.9. Geotextiles in stormwater treatment	80
	3.10. Geotextiles in embankment ponds	82
	3.11. Filtration design	83
	3.12. Drains	84
	3.13. Summary of the main points	87
	3.14. Common questions and their answers	87
	References	88
04	Retaining walls – limit-equilibrium-based approach	93
	<i>B. M. Das and S. K. Shukla</i>	
	4.1. Introduction	93
	4.2. Design considerations	93
	4.3. Design procedure for retaining walls with geotextile reinforcement	96
	4.4. Design procedure for retaining walls with geogrid reinforcement	101
	4.5. Self-evaluation questions	102
	4.6. Summary of the main points	103
	4.7. Common questions and their answers	103
	References	103

05	Retaining walls – reliability-based approach <i>A. Pain and E. Agarwal</i> 5.1. Introduction 5.2. Reliability-based approach 5.3. Methods of reliability-based analysis 5.4. Design procedure for the reliability-based approach 5.5. System probability of failure (P_f) 5.6. Illustrative examples 5.7. Summary of the main points 5.8. Common questions and their answers References	105 105 105 105 107 109 109 112 112 113
06	Embankments <i>E. M. Palmeira</i> 6.1. Introduction 6.2. Geosynthetics as a basal reinforcement in embankments 6.3. Geosynthetics for drainage in embankments 6.4. Combined use of geosynthetic reinforcement and vertical drainage 6.5. Piled embankments 6.6. Summary of the main points 6.7. Common questions and their answers References	115 115 115 125 128 129 134 135 136
07	Shallow foundations <i>S. K. Shukla</i> 7.1. Introduction 7.2. Reinforcing mechanisms and functions 7.3. Reinforcing patterns 7.4. Modes of failure 7.5. Model tests 7.6. Load-bearing capacity analysis 7.7. Settlement analysis 7.8. Prestressed geosynthetic-reinforced foundations 7.9. Geosynthetic deflection profiles and strain analysis 7.10. Field applications 7.11. Summary of the main points 7.12. Common questions and their answers References	139 139 139 141 141 142 150 156 159 163 165 168 168 169
08	Deep foundations <i>M. Muthukumar and S. K. Shukla</i> 8.1. Introduction 8.2. Factors controlling the performance of encased stone columns 8.3. Deformation analysis of geosynthetic-encased stone columns 8.4. Settlement analysis 8.5. Granular pile anchor 8.6. Summary of the main points 8.7. Common questions and their answers References	173 173 175 175 177 178 179 179 180
09	Unpaved roads <i>P. L. Bourdeau, A. K. Ashmawy, A. Trivedi and S. K. Shukla</i> 9.1. Introduction 9.2. Unpaved road reinforcement 9.3. Design for reinforcement 9.4. Experimental developments 9.5. Numerical formulations 9.6. Summary of the main points 9.7. Common questions and their answers References	181 181 182 185 192 193 194 195 195

10	Paved roads and runways	199
	<i>S. W. Perkins, R. R. Berg and B. R. Christopher</i>	
	10.1. Introduction	199
	10.2. Distress features and their relationship to geosynthetics	199
	10.3. Geosynthetic functions	200
	10.4. History and experimental evidence for base reinforcement	205
	10.5. Summary of critical design variables for base reinforcement	206
	10.6. Design solutions and approaches for base reinforcement	206
	10.7. Geosynthetics in airport runways	209
	10.8. Summary of the main points	209
	10.9. Common questions and their answers	209
	References	211
11	Railway tracks	213
	<i>S. A. Tan, S. K. Shukla and S. S. Nimbalkar</i>	
	11.1. Introduction	213
	11.2. Track components and substructure	213
	11.3. Functions of geosynthetics	216
	11.4. Properties of geosynthetics	219
	11.5. Design procedure	221
	11.6. Installation of geosynthetics	221
	11.7. Case histories in railway track stabilisation	222
	11.8. Geosynthetic drains for track drainage applications	225
	11.9. Summary of the main points	228
	11.10. Common questions and their answers	229
	References	230
12	Slopes – erosion control	231
	<i>T. S. Ingold, M.-H. Li and S. Cuomo</i>	
	12.1. Introduction	231
	12.2. Interaction of rain and river erosion	231
	12.3. Mechanics of surface erosion	232
	12.4. Classification of erosion control systems	232
	12.5. Design approach	234
	12.6. Study of short-term yield factors	235
	12.7. Erosion control performance testing of geosynthetics	237
	12.8. Lifetime cost and the performance of erosion control products	240
	12.9. Summary of the main points	241
	12.10. Common questions and their answers	243
	References	244
13	Slopes – stabilisation	247
	<i>S. K. Shukla, N. Sivakugan, B. M. Das and J. F. Xue</i>	
	13.1. Introduction	247
	13.2. Types and orientations of geosynthetics	248
	13.3. Function of reinforcement against slope failure	248
	13.4. Stability analysis of reinforced slopes	249
	13.5. Design aspects of reinforced slopes	253
	13.6. Model tests	256
	13.7. Stabilisation methods in practice	258
	13.8. Summary of the main points	267
	13.9. Common questions and their answers	268
	References	268
14	Landfills and barriers for contaminant migration	273
	<i>H. Zanzinger, E. Gartung and W. Hornsey</i>	
	14.1. Introduction	273
	14.2. Multi-barrier concept	274
	14.3. Landfill categories	274
	14.4. Basal lining systems	276
	14.5. Components of the composite liner	277

	14.6. Construction of liners	280
	14.7. Leachate collection and removal	282
	14.8. Cover system	283
	14.9. Summary of the main points	286
	14.10. Common questions and their answers	287
	References	287
15	Earth and tailings dams	291
	<i>D. N. Arnepalli, D. N. Singh and S. K. Shukla</i>	
	15.1. Introduction	291
	15.2. Use of conventional materials	291
	15.3. Use of geosynthetics	293
	15.4. Riverbed and bank protection	300
	15.5. Design considerations	301
	15.6. Application of geosynthetics in the construction of tailings dams	301
	15.7. Summary of the main points	306
	15.8. Common questions and their answers	306
	References	307
16	Containment ponds, reservoirs and canals	311
	<i>N. Touze, G. Stoltz and L. Peyras</i>	
	16.1. Introduction	311
	16.2. Historical background	311
	16.3. Design of geosynthetic systems	313
	16.4. Evaluation of the durability of geomembranes	316
	16.5. Leak detection and location	318
	16.6. Case studies	320
	16.7. Summary of the main points	337
	16.8. Common questions and their answers	337
	References	338
17	Ports, waterways and coastal structures	343
	<i>Y. Miyata, R. J. Bathurst and D. Takano</i>	
	17.1. Introduction	343
	17.2. Ports	343
	17.3. Waterways	344
	17.4. Coasts	346
	17.5. Summary of the main points	349
	17.6. Common questions and their answers	349
	References	350
18	Hydraulic and transport tunnels, and shafts	353
	<i>D. Cazzuffi, A. Scuero and G. Vaschetti</i>	
	18.1. Introduction	353
	18.2. Geomembrane systems in hydraulic tunnels	354
	18.3. The exposed liner system	357
	18.4. The covered liner system	360
	18.5. Geomembrane systems in transport tunnels	362
	18.6. Geomembrane systems in shafts	365
	18.7. Summary of the main points	367
	18.8. Common questions and their answers	368
	References	370
19	Geosynthetic-reinforced soil walls and slopes – seismic aspects	371
	<i>R. J. Bathurst, K. Hatami and M. C. Alfaro</i>	
	19.1. Introduction	371
	19.2. Material properties under dynamic loading	371
	19.3. Seismic analysis and the design of walls and slopes	380
	19.4. Physical testing of model walls and slopes	401
	19.5. Seismic buffers	406
	19.6. Observed performance of reinforced soil walls and slopes during earthquakes	407

	19.7. Summary of the main points	408
	19.8. Common questions and their answers	409
	References	410
20	Basic description of fibre-reinforced soils	417
	<i>S. K. Shukla</i>	
	20.1. Introduction	417
	20.2. Characteristics of fibre-reinforced soils	419
	20.3. Applications of fibre-reinforced soils	422
	20.4. Summary of the main points	423
	20.5. Common questions and their answers	423
	References	424
21	Sustainability considerations in geosynthetic applications	427
	<i>D. Basu and M. Lee</i>	
	21.1. Introduction	427
	21.2. Sustainability–geotechnical engineering nexus	428
	21.3. Sustainability assessment	430
	21.4. Practice of sustainability in geosynthetics-related projects	445
	21.5. Summary of the main points	452
	21.6. Common questions and their answers	452
	References	453
22	Geosynthetic applications – general aspects and selected case studies	459
	<i>S. K. Shukla</i>	
	22.1. Introduction	459
	22.2. General guidelines for geosynthetic applications	459
	22.3. General guidelines for fibre applications	462
	22.4. Quality control and in situ monitoring	463
	22.5. Cost analysis	466
	22.6. General problems	468
	22.7. Selected case studies	469
	22.8. Summary of the main points	478
	22.9. Common questions and their answers	478
	References	478
	Index	481

Preface

Traditional methods of infrastructure development generate enormous amounts of carbon gases that are released into the atmosphere, increasing the global carbon footprint. Construction activities based on such methods have contributed significantly to global warming and associated geoenvironmental instability worldwide, such as soil erosion, hill/riverbank/coastal slope instability, ice/glacier melting, floods and sea level rise. The COVID-19 pandemic has emphasised the need to develop more-innovative and cost-effective solutions with state-of-the-art technologies, mainly based on the utilisation of locally available and reusable materials.

Geosynthetics help conserve energy and promote more-durable and sustainable structures. The use of geosynthetics assists in reducing the carbon footprint contributed by infrastructure development while minimising the use of natural resources and transported materials. Many field examples have been presented that show the benefits to be low cost, enhanced longevity, resilience and the safety of critical infrastructure, all because of the many special features of geosynthetics, including non-corrosiveness, long-term durability under soil cover, high resistance to biological and chemical degradation, lightness, high flexibility, installation simplicity and quick construction. In view of these advantages, over the past 45–50 years, engineers have shown increasing interest in geosynthetics and their field applications.

Geosynthetics support sustainable developments in several areas of our life, including civil engineering (geotechnical, transportation, environmental and hydraulic), mining, agricultural and aquacultural engineering. These materials, which include geonaturals and fibres available locally, contribute significantly to achieving several of the sustainable development goals of the United Nations (UN), recommended by UN member states in 2015 as a way to preserve the Earth's health using sustainable development.

Geosynthetics and Their Applications, the title of the first edition of this book, was published in 2002. This third edition of the *ICE Handbook of Geosynthetic Engineering* includes many new updates throughout, with five new chapters. Some key features and updates are given below

- Chapter 1: Fundamentals of geosynthetics. Photographs of some new geosynthetic samples have been provided. The list of test standards in Section 1.8 has been updated.
- Chapter 2: Soil–geosynthetic interaction. This now covers the effects of cyclic loading on soil–geosynthetic interface behaviour in detail.
- Chapter 3: Filters and drains. New sections dealing with filter evaluation, the hydraulic compatibility of geotextile filters with industrial by-products, and geotextiles in stormwater and embankment ponds have been added, with several new illustrations.
- Chapter 4: Retaining walls – limit-equilibrium-based approach. A construction site observation has been added, and a case study from Indonesia has been described.
- Chapter 5 (new): Retaining walls – reliability-based approach. This is a new chapter that presents a reliability-based design approach to geosynthetic-reinforced retaining walls with granular backfills by using the first-order reliability method. The steps involved in the reliability-based design are explained through illustrative examples.

-
- Chapter 7: Shallow foundations. Details of Shukla's wraparound reinforcement technique, recently established for strengthening the shallow foundations, have been provided.
 - Chapter 8 (new): Deep foundations. This new chapter has been included to cover the basic concepts and design philosophy of the application of geosynthetics for encasing stone columns/ granular piles. Encased granular anchor piles are also briefly described.
 - Chapter 9: Unpaved roads. Two new sections dealing with experimental developments and numerical formulations have been added.
 - Chapter 10: Paved roads and runways. Details of the applications of geosynthetics in airport runways are provided in the new Section 10.7.
 - Chapter 11: Railway tracks. Section 11.3.3 on confinement/ reinforcement has been updated with mathematical concepts based on the hoop tension theory, in addition to the inclusion of a recent case study on the application of geosynthetics in railway tracks.
 - Chapter 12: Slopes – erosion control. This includes new illustrations and a field study.
 - Chapter 13: Slopes – stabilisation. Section 13.4 on the stability analysis of reinforced slopes has been significantly updated with details on the use of software focusing on correct mesh size selection.
 - Chapter 14: Landfills and barriers for contaminant migration. New illustrations explain several practical aspects of project sites.
 - Chapter 15: Earth and tailing dams. The new Section 15.6 provides details on tailing dams.
 - Chapter 16: Containment ponds, reservoirs and canals. The new Section 16.5 covers leak detection and location. Details on an experimental pond have also been provided.
 - Chapter 17 (new): Ports, waterways and coastal structures. This new chapter considers applications of geosynthetics for quay walls, breakwaters, river embankments, waterfront retaining walls, coastal dykes and groins.
 - Chapter 18: Hydraulic and transport tunnels, and shafts. Transport tunnels and shafts are new additions to this chapter, with several practical illustrations.
 - Chapter 20 (new): Basic description of fibre-reinforced soils. This new chapter presents an overview of the essential characteristics of fibre-reinforced soils with an introduction to their possible field applications.
 - Chapter 21 (new): Sustainability considerations in geosynthetic applications. This new chapter highlights the concept of sustainability in the context of geotechnical engineering with reference to the reliability and resilience of geo-structures and geo-systems. Examples of sustainable practices along with the methods of sustainability assessment are discussed, with particular emphasis on the use of geosynthetics.
 - Chapter 22: Geosynthetic applications – general aspects and selected case studies. The new Section 22.3 provides general guidelines for fibre applications. Details on the major codes of practice for geosynthetic applications have been updated.

Although the subject of geosynthetics is an expanding field, it is generally not taught, especially at the undergraduate level, in engineering and technical colleges as a full subject. Therefore, students, researchers and practising engineers need the basic concepts of geosynthetics and their applications in a simple, presentable form. Current details of geosynthetic applications with a description of case studies and practical aspects are required for quick reference in connection with studying and obtaining solutions to specific field and research problems. Keeping these pressing needs in view as key features, the new edition of the *ICE Handbook of Geosynthetic Engineering* has been written as a single volume with several new chapters, retaining all the features of its previous two editions published in 2002 and 2012. I sincerely hope that this ICE handbook will be a useful tool for engineering professionals, including engineering students, researchers and practising engineers.

I would like to extend special thanks and recognition to the authors of all the chapters for their valuable contributions to meet the needs of users of geosynthetics. I am truly grateful to them.

I would like to thank James Hobbs, Melanie Bell, Madhubanti Bhattacharyya and other staff of ICE Publishing for their full support and cooperation at all the stages of the preparation and production of this handbook.

I wish to extend sincere appreciation to my wife, Sharmila, for her encouragement and support throughout the preparation of the typescript. Thanks also to my daughter, Sakshi, and my son, Sarthak, for their patience during my work on this book at home.

Finally, I welcome suggestions from the readers and users of this book for improving its content in future editions.

Sanjay Kumar Shukla
Perth, August 2021

About the editor



Dr Sanjay Kumar Shukla is the Founding Editor-in-Chief of the *International Journal of Geosynthetics and Ground Engineering*, Springer Nature, Switzerland. He is the Founding Research Group Leader (Geotechnical and Geoenvironmental Engineering) at the School of Engineering, Edith Cowan University, Joondalup, Perth, Australia.

He has over 25 years of experience in teaching, research and consultancy in the field of civil (geotechnical) engineering. He holds the Distinguished Professorship in Civil Engineering at Delhi Technological University, Delhi; VIT University, Vellore; Chitkara University, Solan; VR Siddhartha Engineering College, Vijayawada; Amity University, Noida; Amrita University, Coimbatore; and Nirma University, Ahmedabad, India. He collaborates with several world-class universities, research institutions, industries and individuals on academic and field projects. As a consulting geotechnical engineer, he has successfully provided solutions to the challenging field problems faced by many engineering organisations.

He has authored more than 275 research papers and technical articles, including over 170 refereed journal publications, and serves on the editorial boards of several international journals. He is also the author/editor of 21 books, including seven textbooks, and 12 book chapters. In 2020/2021, his ICE textbooks, namely *Core Principles of Soil Mechanics* and *Core Concepts of Geotechnical Engineering*, were ranked No. 1 by Amazon. His research and academic works are frequently cited. His generalised expressions for seismic active thrust (2015) and seismic passive resistance (2013) are routinely used by practising engineers worldwide for designing retaining structures. His wraparound reinforcement technique, developed during 2007–2008, is a well-established ground improvement technique.

He has been honoured with several awards, including the prestigious IGS Award 2018 from the International Geosynthetics Society, USA, in recognition of his outstanding contribution to the development and use of geosynthetics. He is a fellow of Engineers Australia, a Life Fellow of the Institution of Engineers (India) and the Indian Geotechnical Society, a member of the American Society of Civil Engineers, the International Geosynthetics Society and several other professional bodies.

List of contributors

E. Agarwal

Geotechnical Engineering Group, CSIR – Central Building Research Institute, Roorkee, India, and Academy of Scientific and Innovative Research (AcSIR), Ghaziabad, India

M. C. Alfaro

Department of Civil Engineering, University of Manitoba, Winnipeg, Canada

D. N. Arnepalli

Department of Civil Engineering, Indian Institute of Technology Madras, Chennai, India

A. K. Ashmawy

School of Engineering, American University, Dubai, UAE

A. H. Aydilek

Department of Civil and Environmental Engineering, University of Maryland, College Park, Maryland, USA

D. Basu

Department of Civil and Environmental Engineering, University of Waterloo, Waterloo, Canada

R. J. Bathurst

GeoEngineering Centre at Queen's – RMC, Department of Civil Engineering, Royal Military College of Canada, Kingston, Canada

R. R. Berg

Ryan R. Berg and Associates, Woodbury, Minnesota, USA

P. L. Bourdeau

School of Civil Engineering, Purdue University, West Lafayette, Indiana, USA

D. Cazzuffi

CESI, Milano, Italy

B. R. Christopher

Christopher Consultants, St Augustine, Florida, USA

S. Cuomo

Geotechnical Engineering Group (GEG), University of Salerno, Fisciano, Italy

B. M. Das

College of Engineering and Computer Science, California State University, Sacramento, Long Beach, California, USA

A. Y. Dayioglu

Department of Civil Engineering, Istanbul Technical University, Istanbul, Turkey

E. Gartung

LGA – Geotechnical Institute, Nuremberg, Germany

K. Hatami

School of Civil Engineering and Environmental Science, University of Oklahoma, Norman, Oklahoma, USA

W. Hornsey

TRI Australasia, Burleigh Heads, Australia

T. S. Ingold

Consulting Geotechnical Engineer, St Albans, UK

M. Lee

Department of Civil and Environmental Engineering, University of Waterloo, Waterloo, Canada

M.-H. Li

School of Planning, Design and Construction, Michigan State University, East Lansing, Michigan, USA

M. L. Lopes

CONSTRUCT-GEO, Faculty of Engineering, University of Porto, Porto, Portugal

Y. Miyata

Department of Civil Engineering, National Defense Academy of Japan, Yokosuka, Japan

M. Muthukumar

Department of Structural and Geotechnical Engineering, School of Civil Engineering, Vellore Institute of Technology (VIT), Vellore, India

S. S. Nimbalkar

School of Civil and Environmental Engineering, University of Technology Sydney, Sydney, Australia

A. Pain

Geotechnical Engineering Group, CSIR – Central Building Research Institute, Roorkee, India, and Academy of Scientific and Innovative Research (AcSIR), Ghaziabad, India

E. M. Palmeira

Department of Civil and Environmental Engineering, University of Brasília, Brasília, Brazil

S. W. Perkins

Department of Civil Engineering, Montana State University, Bozeman, Montana, USA

L. Peyras

INRAE, Aix-Marseille University, RECOVER Unit, Aix-en-Provence, France

A. Scuro

Carpi Tech, Balerna, Switzerland

S. K. Shukla

Geotechnical and Geoenvironmental Engineering Research Group, School of Engineering, Edith Cowan University, Joondalup, Australia

D. N. Singh

Department of Civil Engineering, Indian Institute of Technology Bombay, Mumbai, India

N. Sivakugan

Discipline of Civil and Environmental Engineering, School of Engineering and Physical Sciences, James Cook University, Townsville, Australia

G. Stoltz

INRAE, Aix-Marseille University, RECOVER Unit, Aix-en-Provence, France

D. Takano

Geotechnical Engineering Division, Port and Airport Research Institute, Yokosuka, Japan

S. A. Tan

Department of Civil Engineering, National University of Singapore, Singapore

N. Touze

University of Paris-Saclay, INRAE, SDAR, Jouy-en-Josas, France

A. Trivedi

Department of Civil Engineering, Delhi Technological University, Delhi, India

G. Vascetti

Carpi Tech, Balerna, Switzerland

C. S. Vieira

CONSTRUCT-GEO, Faculty of Engineering, University of Porto, Porto, Portugal

J. F. Xue

School of Engineering and Information Technology, University of New South Wales, Canberra, Australia

H. Zanzinger

SKZ – Testing, Wuerzburg, Germany

Y. Zhang

School of Transportation, Southeast University, Nanjing, China